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Techno-economic analysis of energy renovation measures for a district heated multi-family house

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HIGHLIGHTS

- Energy saving measures can be cost-effective as part of a planned renovation.
- Primary energy consumption, non-renewable energy consumption and CO_2 emissions are assessed for different electricity mixes.
- EAHP can be a cost-effective and environmentally beneficial complement to district heating.
- EAHP has lower LCC and significantly shorter payback time than ventilation with heat recovery.
- Low-temperature ventilation radiators improve the COP of the heat pump.

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ABSTRACT

Renovation of existing buildings is important in the work toward increased energy efficiency and reduced environmental impact. The present paper treats energy renovation measures for a Swedish district heated multi-family house, evaluated through dynamic simulation. Insulation of roof and façade, better insulating windows and flow-reducing water taps, in combination with different HVAC systems for recovery of heat from exhaust air, were assessed in terms of life cycle cost, discounted payback period, primary energy consumption, CO_2 emissions and non-renewable energy consumption. The HVAC systems were based on the existing district heating substation and included mechanical ventilation with heat recovery and different configurations of exhaust air heat pump.

Compared to a renovation without energy saving measures, the combination of new windows, insulation, flow-reducing taps and an exhaust air a heat pump gave up to 24% lower life cycle cost. Adding insulation on roof and façade, the primary energy consumption was reduced by up to 58%, CO_2 emissions up to 65% and non-renewable energy consumption up to 56%. Ventilation with heat recovery also reduced the environmental impact but was not economically profitable in the studied cases. With a margin perspective on electricity consumption, the environmental impact of installing heat pumps or air heat recovery in district heated houses is increased. Low-temperature heating improved the seasonal performance factor of the heat pump by up to 11% and reduced the environmental impact.

1. Introduction

District heating (DH) is well established in Sweden, serving around 85% of the dwellings in multi-family houses [1]. This is a high share in a European context, although in Denmark, Finland and the Baltic countries DH systems serve more than 50% of the citizens [2]. In total, there are 2.4 million dwellings in multi-family houses in Sweden, 75% of which are more than 40 years old [3]. This suggests a need for renovation, and a great potential for energy savings [4,5]. 68% of the multi-family houses built within the period 1961–1980 have a mechanical exhaust ventilation system, while ventilation with heat recovery increased in popularity during 1981–2000 [6]. The DH in Sweden is, on average, to 87% derived from recovery of excess heat or from renewable fuels [7]. The share of fossil fuels is higher during starts and stops in production, which are required to meet the variations in demand [8,9].

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Nomenclature

CO_2	carbon dioxide
COP	coefficient of performance
DH	district heating
DHW	domestic hot water
DPB	discounted payback
EAHP	exhaust air heat pump
HVAC	heating, ventilation and air conditioning
LCC	life cycle cost
LCCA	life cycle cost analysis
MVHR	mechanical ventilation with heat recovery
NRE	non-renewable energy
PEC	primary energy consumption
PEF	primary energy factor (kW h/kW h)
RE	renewable energy
SFP	specific fan power (W/(l s))
SPF	seasonal performance factor
U	heat transfer coefficient for building parts (W/(m^2 K))

Moreover, there is typically a regional variation, for DH as well as for electricity, in how energy is produced and what the resulting CO_2 emissions, non-renewable energy (NRE) consumption and primary energy consumption (PEC) are [7,10]. The total PEC is also dependent on the conversion factor. For example, heat production has a higher conversion factor than electricity production.

Although energy renovation of buildings is deemed a key in the work toward increased energy efficiency in the European Union [11], energy renovation of district heated buildings is a complicated matter for a number of reasons, including the relatively high share of renewable energy in DH production and the cogeneration of heat and electricity in many DH plants. In a system perspective it can often be better to reduce the electricity consumption than the heating demand, since reducing the heating demand of a district heated building could deteriorate the conditions for electricity production [12–14]. However, from the building owner's perspective it can be interesting to take energy saving measures in conjunction with a renovation to reduce the energy costs. Improving the energy performance of a house can also have positive effects on the indoor climate [15] and increase the value of the building [16]. Future district heating systems are likely to have a lower distribution temperature, 50–60 °C rather than today's 70–90 °C [17–20], to meet the needs of new and renovated buildings with low heating demand. As a result, the district heating temperature will also be better suited for low-temperature heating systems, such as floor heating or low-temperature radiators, with distribution temperatures of 35–45 °C [21].

Previous studies by Gustafsson et al. [22,23] have shown that exhaust air heat pump (EAHP) and mechanical ventilation with heat recovery (MVHR) can both be beneficial solutions, with respect to cost and energy consumption, for energy renovation of single family houses in northern and central Europe, and that the advantage of heat recovery from exhaust air becomes larger in cold climates. Furthermore, these studies showed that low-temperature radiator systems improve the energy performance of heat pumps. Liu et al. [24] studied energy saving measures for multi-family houses in Gävle, Sweden. The study showed promising technical potential, although many of the studied measures were deemed unprofitable, in particular façade insulation, windows with low U-value and MVHR. This, however, was based on a reference case where no renovation was done to the building. They also pointed at the need for more research on EAHP as an alternative to MVHR, especially in leaky buildings where the MVHR would struggle to achieve a good level of efficiency. Truong et al. [25] and Gustavsson et al. [26] discussed, also in a Swedish context, the complexity of evaluating effects of energy saving measures in buildings with district heating, pointing at the importance of the interaction between end-use measures and supply systems. Truong et al. [25] and Dodoo et al. [27] concluded that MVHR could lead to significant savings of primary energy in a Swedish climates, although without comparison with EAHP as an alternative heat recovery system. The potential primary energy savings were shown to be larger in houses with direct electric heating than in district heated houses [27], and the size of the savings in district heated houses depend on the energy mix in the local DH production [25].

The present study complements the existing research on renovation of residential buildings, investigating environmental and economic aspects of HVAC systems with air heat recovery and measures to reduce the energy demand of a district heated multi-family house. The studied HVAC systems included three systems with EAHP together with DH in different configurations: EAHP used for space heating or for both space heating and domestic hot water (DHW) production, including one variant with a low-temperature radiator system. The three heat pump systems, plus one system with MVHR, were compared against a reference system with only DH and exhaust ventilation without heat recovery. All systems were evaluated in combination with two sets of energy renovation measures: better insulating windows and flow reducing water taps, and insulation on roof and façade. The aim of this study was to investigate the possible economic incentives and environmental benefits for owners of district heated houses to perform energy efficiency measures as part of a planned renovation.

The renovation measures were assessed in terms of life cycle cost (LCC), discounted payback (DPB) time and, with respect to the European climate and energy goals [28], CO_2 emissions, PEC and NRE consumption. For NRE, the EU goal is formulated as a target share of 27% renewable energy sources. Here, both the total amount of NRE and the non-renewable share of the total energy consumption were considered.

The building and the HVAC systems were modelled and simulated in TRNSYS 17 [29]. All HVAC systems were designed to provide space heating, DHW and ventilation, while cooling was left out of the scope. Likewise, periodic time variations of energy prices and of environmental factors were disregarded in this study, but the impact of economic factors and different assumptions on electricity production was investigated.

2. Building and system models

The building model used in this study represented a four-story residential building, with a heated area, including stairwells, of 4700 m^2. Most of the 2340 m^2 brick façade and the 700 m^2 windows and doors were oriented toward east and west, as shown in Fig. 1. The roof had an area of 1210 m^2 and 4° inward inclination along the central line. In the model, there were nine zones for the living area – three zones per floor on three floors, each zone comprising three apartments – plus three zones for the stairwells and one for the unheated attic. To get results for a complete floor (15 apartments), adiabatic connection to adjacent zones was assumed and the results of the middle living zone and stairwell were multiplied by three, as illustrated in Fig. 1. Similarly, to get results for